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Measurement of the slope parameter of beauty baryon form factor

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Abstract

The slope of the form factor of b -baryons is estimated using 2.710^6 hadronic Z decays collected by the DELPHI experiment between 1992 and 1994. In a first step, charmed Λ_c^+ baryons are fully reconstructed in the $pK^-\pi^+$ mode. These Λ_c^+ baryons are then associated to an opposite sign lepton (electron or muon) in order to select $\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l$ decays. Estimates of the neutrino energy and of the Λ_b direction allow to reconstruct the distribution of the $w = v_{\Lambda_b} \cdot v_{\Lambda_c}$ variable of 29 selected events. From a binned χ^2 fit to this w distribution, the slope of b -baryon form factor is measured to be :

$$\hat{\rho}^2 = 1.81 \begin{smallmatrix} +0.70 \\ -0.67 \end{smallmatrix} \text{ (stat.) } \pm 0.32 \text{ (syst.)}$$

1 Introduction

In the sector of the b quark, mesons have been quite extensively studied at $\Upsilon(4S)$ and LEP energies : masses, lifetimes and most of the branching ratios are now well measured. Recent publications also present results on the beauty mesons form factor [1]. On the other hand there is less information on beauty baryons, and this note provides a first estimate of the slope of the b -baryon form factor.

Section 2 summarises the form factor formalism and introduces the relevant variable w . The experimental analysis presented in the next sections is based on the study of Λ_b semileptonic decays : $\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l$, with $l^- = \mu^-$ or e^- ¹. Section 3 presents the Λ_c^+ reconstruction in the $pK^-\pi^+$ mode, followed by the description of Λ_c -lepton association. Section 4 presents the w reconstruction algorithm and the results of the fit to the w distribution. In Section 5, these results are summarized and compared to theoretical predictions and experimental results which are available on beauty mesons.

2 Beauty baryons form factor

A complete description of the form factor formalism and theoretical expectations can be found in ref. [2] [3] [4]. This section presents a brief summary of needed basics.

The current which describes the weak decay of a beauty particle to a charmed particle involves three form factors in the case of mesons (e.g. $\bar{B}_d^0 \rightarrow D^{*+}W^-$) and six form factors in the case of baryons (e.g. $\Lambda_b \rightarrow \Lambda_c^+ W^-$). In the limit of infinite b and c quarks masses, only one universal function $\xi(q^2)$ is needed, where q^2 is the squared four momentum transfer from the beauty particle to the charmed particle :

$$q^2 = (p_{\Lambda_c^+} - p_{\Lambda_b})^2$$

In this Heavy Quark Effective Theory (HQET) framework, the shape of this Isgur-Wise function $\xi(q^2)$ is not predicted, and a linear expansion is usually assumed :

$$\xi(q^2) = \xi(q_{max}^2) \left(1 + a^2 \frac{q_{max}^2 - q^2}{2m_{\Lambda_b} m_{\Lambda_c}} + \mathcal{O}(1/m_{b,c}) \right)$$

This function can be rewritten using the four velocities of the Λ_b and the Λ_c :

$$w = v_{\Lambda_b} \cdot v_{\Lambda_c} = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2)/(2m_{\Lambda_b} m_{\Lambda_c})$$

$$\xi(w) = \xi(w \rightarrow 1) \left(1 - \hat{\rho}^2(w - 1) + \mathcal{O}((w - 1)^2) \right)$$

As an example, w values associated to the decay $\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l$ can range from 1 (highest transfer) to a value close to 1.44 (smallest transfer, $q^2 = 0$). In the absence of mass dependent corrections, the flavor independence of QCD implies that $\xi(w \rightarrow 1)$ is normalized to 1. Taking into account $(\Lambda_{QCD}/m_c)^2$ corrections and perturbative QCD effects [2]), we will use $\xi(w \rightarrow 1) = 0.91 \pm 0.04$.

¹Charge conjugation is implicitly assumed in this work and both $\Lambda_c^+ l^-$ and $\Lambda_c^- l^+$ are selected

Theoretical predictions and experimental results available in the meson sector are :

$$\begin{aligned}\hat{\rho}^2 &= 0.9 \quad {}^{+0.6}_{-0.5} \quad (\text{lattice QCD [3]}) \\ \hat{\rho}^2 &= 0.9 \pm 0.3 \quad (\text{QCD sum rules [4]})\end{aligned}$$

$$\hat{\rho}^2 = 0.75 \pm 0.17 \pm 0.10 \quad (\text{DELPHI, } \overline{B}_d^0 \rightarrow D^{*+} l^- \overline{\nu}_l \text{ [5]})$$

To measure this slope in the baryonic channel, the semileptonic decay $\Lambda_b \rightarrow \Lambda_c^+ l^- \overline{\nu}_l$ will be used (the semileptonic decay allows the extraction of V_{cb} with the smallest theoretical uncertainty in the mesonic channel [5]). The differential decay width of this process can be calculated from [2] :

$$\frac{d\Gamma}{dw} = G K(w) \xi^2(w)$$

G contains coupling factors such as G_F and V_{bc} , and $K(w)$ is a kinematical factor which depends on the nature of the involved particles :

$$G(w) = \frac{2}{3} \frac{G_F^2}{(2\pi)^3} |V_{cb}|^2 m_{\Lambda_c}^2$$

$$K(w) = q^2 P \left(2w + \frac{(m_{\Lambda_b}^2 + m_{\Lambda_c}^2)w - 2m_{\Lambda_b}m_{\Lambda_c}}{q^2} \right) \quad \text{with} \quad P = m_{\Lambda_c} \sqrt{w^2 - 1}$$

From the experimental point of view, the reconstructed w distribution of N selected Λ_c -lepton events will be compared to the one predicted by the simulation. The G term will be accounted for through the normalisation of the simulated events to the number of real data events, and the $K(w)$ factor will be automatically taken into account by the generation of the simulated events.

3 Event selection

3.1 $\Lambda_c^+ \rightarrow p K^- \pi^+$ selection

The Λ_c^+ baryons are selected in the $\Lambda_c^+ \rightarrow p K^- \pi^+$ mode using 92 to 94 data. The selection is briefly described below, and a more complete description can be found in [7].

After a standard hadronic event selection, triplets of charged tracks of total charge unity are selected. Each track is requested to have at least one hit in the microvertex detector. The momenta are required to be larger than 3 GeV/c (proton candidate), 2 GeV/c (kaon candidate) or 1 GeV/c (pion candidate), and the total momentum is required to be larger than 8 GeV/c. The mass of the Λ_c candidate should lie in the 2.1-2.5 GeV/c² range. A secondary vertex is fitted with these three tracks, requiring a χ^2 probability larger than 0.001. A primary vertex is also fitted using a standard procedure starting from all tracks of the event. The Λ_c flight is computed as the difference between the secondary and the primary vertex. This flight is signed with respect to the momentum direction of the triplet and it is required to be positive.

HADSIGN flags are used to identify the proton and the kaon in 1992 and 1994 data. It was decided to use only RICH information to identify the proton and the kaon in 1993 data

because this insures a better signal to noise ratio. No identification cut is applied to the pion candidate. The efficiencies associated to proton and kaon identification are obtained on dedicated samples of real data, namely Λ^0 (for the proton) and $D^{*\pm}$ reconstructed in the $K\pi\pi$ mode (for the kaon). The proton and kaon efficiencies are obtained for different momentum ranges, and these are convoluted with the momentum distributions of protons and kaons from Λ_c decays to get the overall Λ_c identification efficiencies : $(40.1 \pm 8.7)\%$ (1992 data), $(21.5 \pm 4.8)\%$ (1993 data), $(51.1 \pm 10.7)\%$ (1994 data). These numbers, *estimated from real events*, correspond to identification efficiencies only and do not include the efficiencies associated to the cuts on momenta or number of microvertex hits of the proton, kaon and pion candidates.

3.2 Λ_c^+ lepton pairing

The second step consists in the selection of standard leptons (electrons or muons) with a momentum larger than 3 GeV/c and a transverse momentum p_t larger than 0.6 GeV/c. The transverse momentum is computed with respect to the lepton jet after rejection of the lepton from this jet (i.e. $p_t = p_t^{out}$). The efficiency associated to this selection is taken from the simulation.

The leptons are paired with opposite sign Λ_c , requiring a total momentum larger than 18 GeV/c and a total mass above 3.5 GeV/c² (muons) or 3.2 GeV/c² (electrons) to ensure a good rejection of possible $B \rightarrow \Lambda_c^+ l^- \nu X$ decays. The Λ_c^+ -lepton vertex is fitted and the resulting flight with respect to the primary vertex is signed according to the total momentum direction, and required to be positive. The reconstruction efficiency ϵ_{rec} associated to the Λ_c -lepton selection is estimated from simulated $\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l$ events to be $(7.82 \pm 0.15)\%$. This number, *estimated from simulated events*, includes the efficiency associated to the lepton selection and identification, the efficiency associated to the cuts on the Λ_c momentum and flight, and the efficiency associated to the cuts on the momenta and number of microvertex hits of the proton, kaon and pion candidates.

Figure 1 shows the invariant mass distributions of Λ_c candidates accompanied by a lepton for good sign ($\Lambda_c^\pm l^\mp$) and wrong sign ($\Lambda_c^\pm l^\pm$) combinations. From the 2.7 million hadronic Z^0 events collected between 1992 and 1994, a clear signal of 33.7 ± 7.2 events is seen over a small background. The fitted Λ_c mass is 2.285 ± 0.003 GeV/c² compatible with the PDG value [6]. The width of the signal is found to be 9.9 ± 2.7 MeV/c².

4 w reconstruction and fit to the w distribution

4.1 w reconstruction

The energy of the undetected neutrino is estimated from a procedure which was already used in the study of mesons [5]. The total energy E_{same} seen in the Λ_c^+ hemisphere is subtracted from the expected hemisphere energy ($\sqrt{s}/2$). The resulting missing energy is corrected in a first step with real data using the observed masses of the Λ_c^+ hemisphere and of the opposite hemisphere, and in a second step by using a function of the hemisphere energy determined from the simulation :

$$E_{miss} = \sqrt{s}/2 - E_{same} + \frac{m_{same}^2 - m_{oppo}^2}{2\sqrt{s}}$$

$$E_{\bar{\nu}_l} = E_{miss} + f_{sim}(E_{same})$$

The first correction accounts for events which have more than two jets, the second takes into account detector inefficiencies. $E_{\bar{\nu}_l}$ is set to zero when the procedure described above leads to a negative energy. The resolution finally obtained on the energy of the neutrino is around 33%. Adding this energy to the energy of the Λ_c and of the lepton gives the energy of the Λ_b with a resolution of 11%.

The Λ_b and Λ_c directions are also needed to estimate w . The Λ_c direction is given by its momentum. The Λ_b direction is estimated from its reconstructed flight direction for 1994 data and from the direction of the thrust axis for 1992 and 1993 data. The q^2 and w values can then be estimated for each event. The resolutions achieved for q^2 are comparable to the one obtained in [5] (see Figure 2).

4.2 Fit to the w distribution

In order to obtain the w distribution of data events, w bins are defined and the number of Λ_c is fitted in each of these bins. Two bins can be defined in the physical w range ($1. < w < 1.22$ and $1.22 < w < 1.44$) and one containing unphysical values ($w > 1.44$). The number of Λ_c fitted in each of these three bins are 15.3 ± 4.7 , 7.4 ± 3.7 and 7.0 ± 3.4 respectively (see Figure 3). Their sum is called $N_{real,recons.,id.}$ and is found to be 29.7 ± 6.9 which is compatible with the result obtained by the fit to the total number of events (33.7 ± 7.2). The numbers obtained in each bin are *corrected for identification efficiency* using for the identification efficiency a mean value of $40.8 \pm 16.1\%$ computed on the basis of the efficiencies given in Section 3.1. This gives 37.5 ± 11.5 , 18.1 ± 8.9 and 17.1 ± 8.2 , where the errors are statistical only and do not include the error on the identification efficiencies. The sum of these last numbers is called $N_{real,recons.}$ and is equal to 72.7 ± 16.1 .

Simulated $\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l$ events are then generated with a flat form factor ($\hat{\rho}^2 = 0$), and these will be reweighted using the slope as a free parameter to get the corresponding predicted w distribution. This simulated sample is normalized to the expected number of reconstructed events ($N_{real,recons.}$) taking into account the production rates, the branching ratios and the reconstruction efficiency :

$$N_{sim,exp} = N_{Z^0} * 2\Gamma_{b\bar{b}} * 2f(b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l) * Br(\Lambda_c^+ \rightarrow pK^- \pi^+) * \epsilon_{rec}$$

In the above formula, the first factor 2 corresponds to the selection of the b or \bar{b} quark, the second corresponds to the selection of muon or electron (τ decays are expected to be rejected by mass and momentum cuts). $\Gamma_{b\bar{b}}$ and $Br(\Lambda_c^+ \rightarrow pK^- \pi^+)$ values are taken from the PDG [6]. $f(b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l)$ stands for $f(b \rightarrow \Lambda_b) * Br(\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l)$ assuming that all beauty mesons have been rejected, and its value is extracted from [8] [9] [10] using the measured value of $f(b \rightarrow b\text{-baryon}) * Br(b\text{-baryon} \rightarrow \Lambda l^- \bar{\nu}_l X)$. We use :

$$\Gamma_{b\bar{b}} = (22.12 \pm 0.20)\%$$

$$f(b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l) = (8.18 \pm 1.39)10^{-3}$$

$$Br(\Lambda_c^+ \rightarrow pK^- \pi^+) = (4.4 \pm 0.6)\%$$

The expected number of reconstructed events from the simulation is then found to be $N_{sim,exp} = 69$, which is compatible with the number of reconstructed events obtained on real data ($N_{real,recons.} = 72.7 \pm 16.1$).

A binned χ^2 fit is then performed between the w distribution obtained with reconstructed data events and the one predicted by the simulation. The comparison performed using the two physical bins leads to :

$$\hat{\rho}^2 = 1.81 \begin{smallmatrix} +0.70 \\ -0.67 \end{smallmatrix} \text{ (stat.)}$$

where the error is statistical only. The associated χ^2 value is 0.15 for one degree of freedom. Performing the fit using the three bins gives $\hat{\rho}^2 = 1.60 \pm 0.62$ (stat.) with $\chi^2 = 1.2$ for two degrees of freedom. It can be seen on Figure 4 that the agreement between data and simulation is worse in the third bin corresponding to the unphysical w values. This may be an indication that the w resolution in the data is not well reproduced by the simulation at small q^2 values, or that there is a remaining contamination of $B \rightarrow \Lambda_c^+ l^- X$ events. The two results are obviously compatible, and the first one will be kept as it corresponds to a better fit.

The systematic error on the first result has been estimated by varying all parameters (production cross sections, branching ratio $Br(\Lambda_c^+ \rightarrow pK^-\pi^+)$, efficiencies) in turn and adding quadratically the variations of the slope parameter. This error is dominated by the uncertainties on the identification efficiencies. The final result is :

$$\hat{\rho}^2 = 1.81 \begin{smallmatrix} +0.70 \\ -0.67 \end{smallmatrix} \text{ (stat.)} \pm 0.32 \text{ (syst.)}$$

Taking into account the statistical error only, it can be stated that $\hat{\rho}^2 > 0$ with 95% confidence level. The systematic error slightly lowers the significance of the result, yet it is still 2.3 standard deviations above zero.

5 Conclusion

Using the $\Lambda_b \rightarrow \Lambda_c^+ l^- \bar{\nu}_l$ decay, a first measurement of the slope of the form factor of the Λ_b beauty baryon was obtained. Assuming a linear expansion of the Isgur-Wise function :

$$\xi(w) = \xi(w \rightarrow 1) \left(1 - \hat{\rho}^2(w - 1) + \mathcal{O}((w - 1)^2) \right)$$

$\hat{\rho}^2$ was determined to be :

$$\hat{\rho}^2 = 1.81 \begin{smallmatrix} +0.70 \\ -0.67 \end{smallmatrix} \text{ (stat.)} \pm 0.32 \text{ (syst.)}$$

Figure 5 shows a comparison of this result to theoretical and experimental results available for beauty mesons. It can be seen on this figure that there is no obvious disagreement between all these results², yet a more precise measurement of the $\hat{\rho}^2$ of beauty baryons will of course be necessary to get further conclusions.

²The slope $\hat{\rho}^2$ should *not* be the same for mesons and baryons, and the relation $\hat{\rho}_{baryon}^2 \sim 2\hat{\rho}_{meson}^2$ can be inferred from crude considerations [11]

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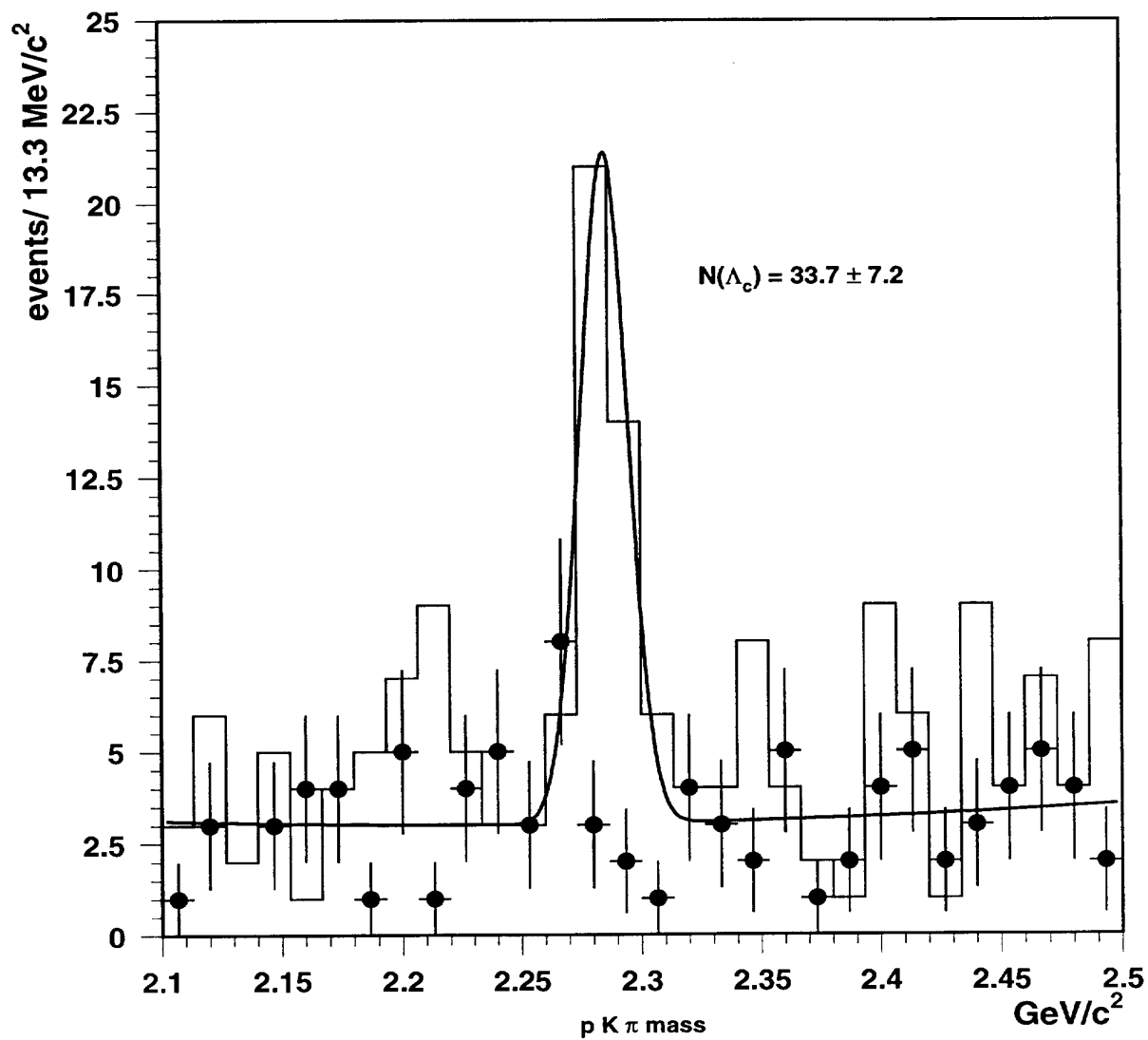


Figure 1: Mass distribution of Λ_c candidates for right sign combinations ($\Lambda_c^\pm l^\mp$, full line) and wrong sign combinations ($\Lambda_c^\pm l^\pm$, black points). The fit is made with a Gaussian shape for the signal and a polynomial shape for the background.

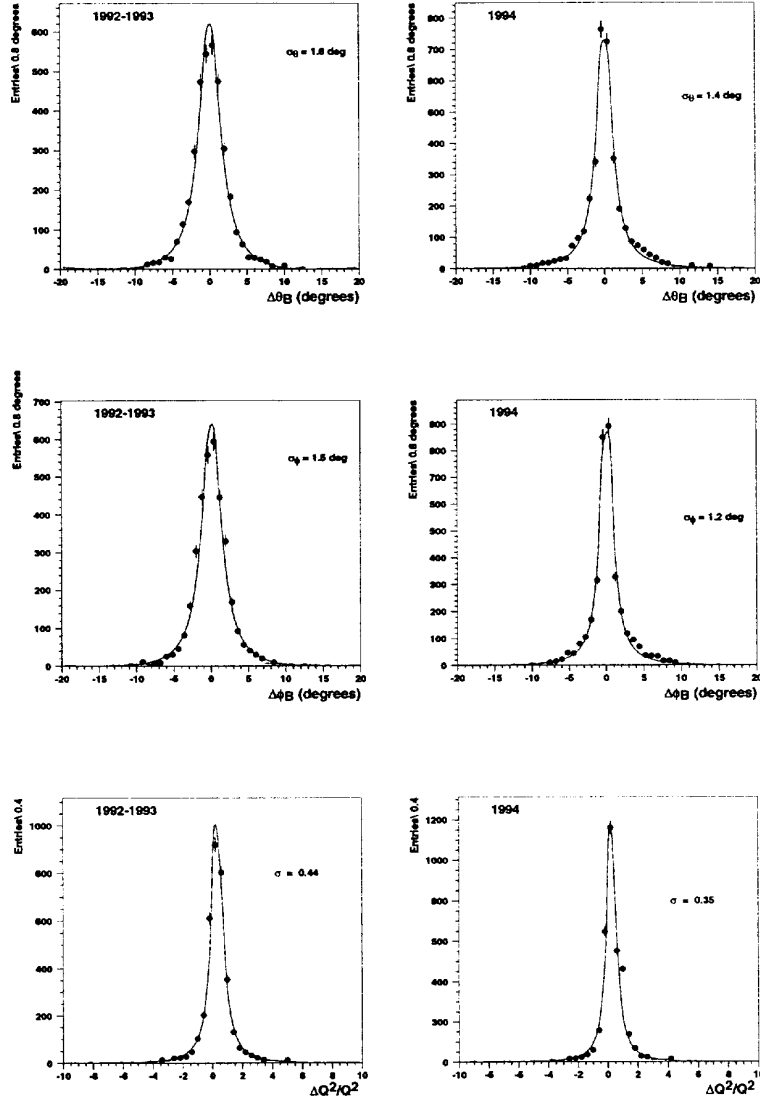


Figure 2: Resolutions achieved in 1992-1993 and 1994 for the reconstruction of angular variables (θ and ϕ) and for the q^2 variable.

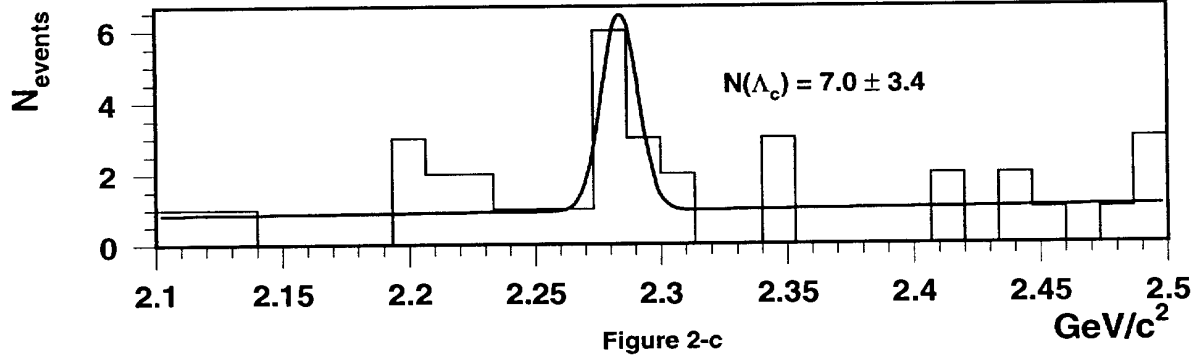
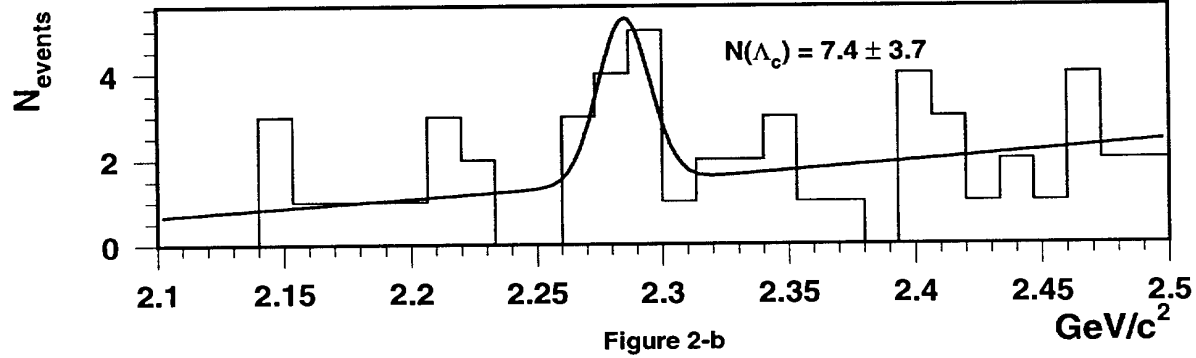
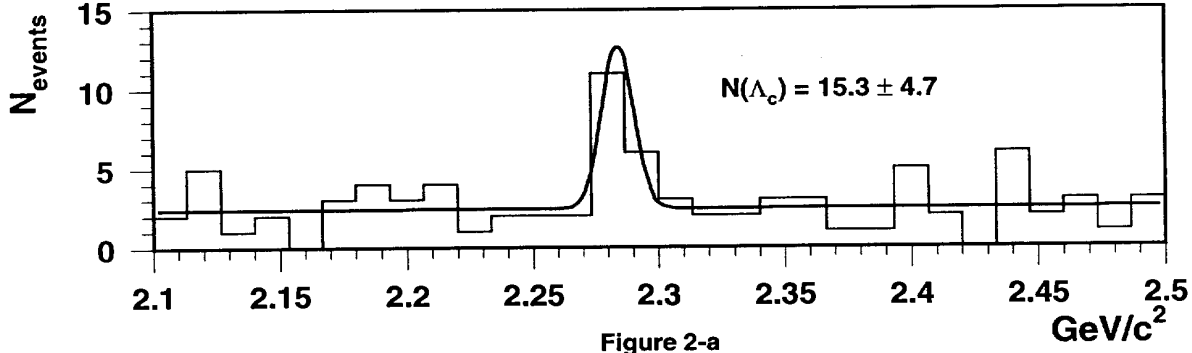


Figure 3: Mass distribution of Λ_c candidates for right sign combinations when $1 < w < 1.22$ (Figure 3-a), $1.22 < w < 1.44$ (Figure 3-b) and $w > 1.44$ (Figure 3-c). The fits are made with a Gaussian shape for the signal and a polynomial shape for the background.

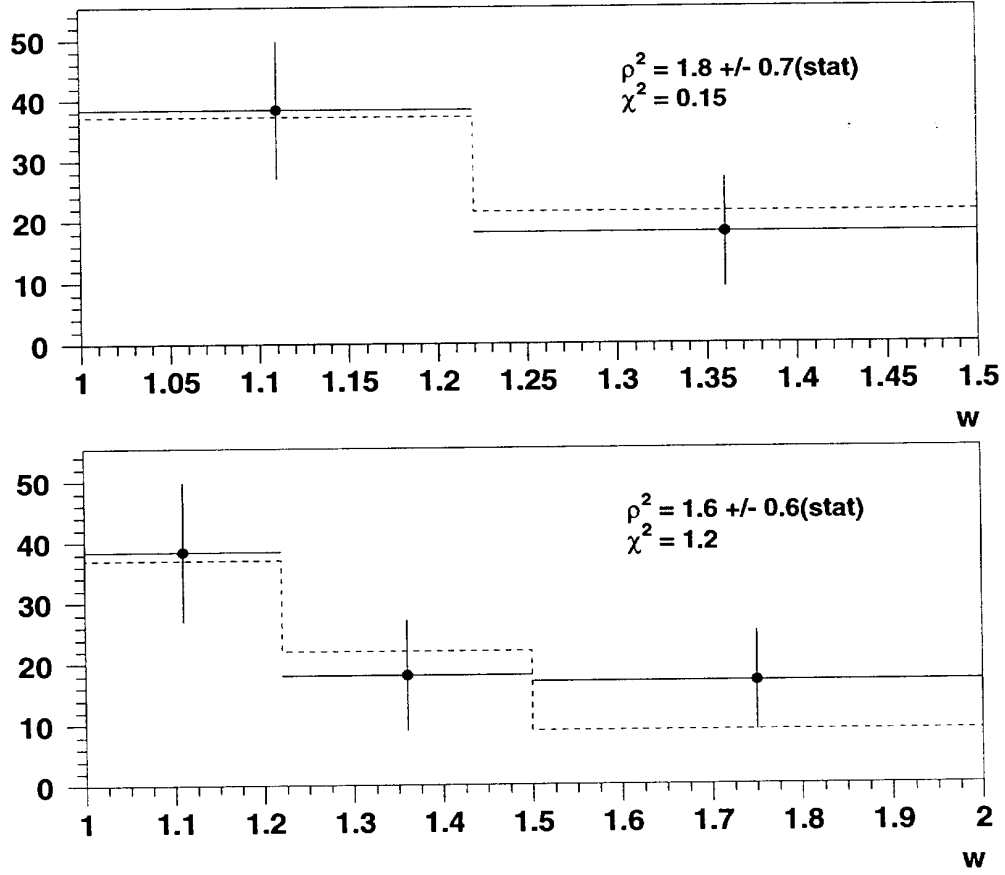


Figure 4: w distributions and fits. The dots represent real data, the histograms correspond to the fitted simulated distributions. Figure 4-a : 2 bins fit in the physical range ($w < 1.44$). Figure 4-b : fit over the whole w range (the last bin contain all events with $w > 1.44$). The errors are statistical only.

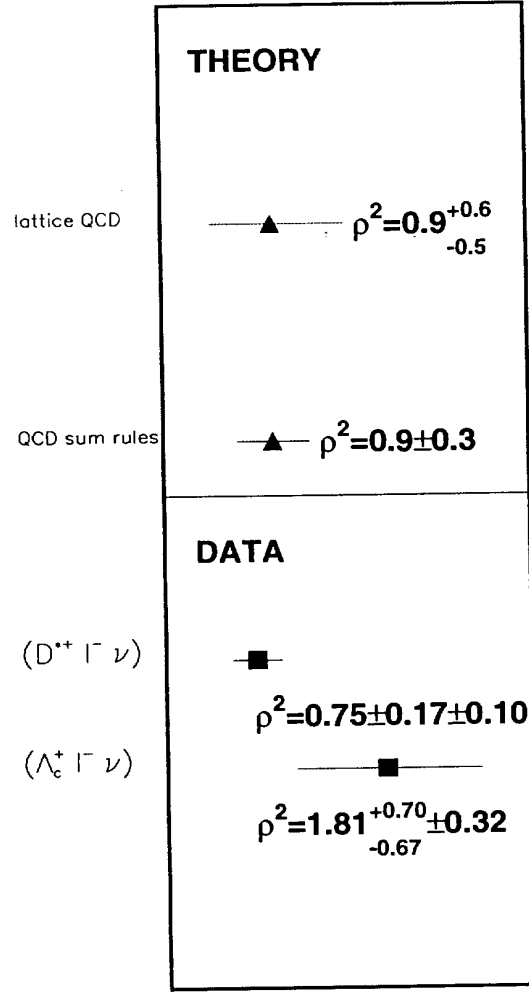


Figure 5: Comparison of the available results : triangles represent theoretical estimations for mesons, squares show the experimental result on mesons and the result obtained here for baryons.